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Streamflow allocation in arid watersheds: a case study in Northwestern China

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Abstract

This paper proposes a framework for allocating water resources among the upper, middle, and lower reaches of arid watersheds to meet the multiple demands for water, including rehabilitation of downstream ecosystem. The framework includes: (1) hydrologic simulation of distribution of water resources in the study watershed; (2) development of water allocation criteria; and (3) implementation of the water allocation plan. The advantages of the proposed framework are: (1) spatial integration; (2) multiple objectives; (3) incorporation of local needs through participatory decision making; and (4) dynamic evaluation.

The framework was applied to the Heihe watershed, a large inland (terminal lake) watershed with a drainage area of over 128 000 km^2 in Northwestern China. Simulation of the daily river flows for the period of 1990–2000 by the Distributed Large Basin Runoff Model shows that Qilian Mountain in the upper reach produced most of the runoff in the watershed, and the increased withdrawals of water for agricultural irrigation, industrial development, and municipal supplies at the middles reach oasis reduced the annual mean discharge by approximately 0.18×10^9 m^3 over the simulation period, making the middle reach unable to deliver the mandated amount of 0.95×10^9 m^3 water downstream by the State Council, under normal climatic conditions. Changes in land use practices need to be implemented to achieve the mandated water allocation plan. The paper suggests that a participatory watershed planning approach involving multiple stakeholders in the water allocation process be undertaken to address key questions regularly, including how much water should be allocated to what uses and for whom and at what price?

1 Introduction

Proper allocation of water resources among competing uses is essential to ensure the welfare of human beings and the sustainability of ecosystems, especially in water stressed regions. Traditionally, multiple approaches have been used in determining water allocations at different scales. At the basin scale, water resources are often allocated through agreements or compacts reached among users in different jurisdictions. For example, the legal and institutional framework for managing the Colorado River, the 1922 Colorado River Compact, allocates water volumes between the Upper Basin States (Colorado, New Mexico, Utah, and Wyoming) and Lower Basin States (Arizona, California, and Nevada) in the United States, with additional water allocated to Mexico (Pontius, 1997). A number of agreements such as the 1994 Jordan-Israel Peace Agreement in the Jordan River Basin and the 1959 Nile Water Treaty, are in place to govern the water allocation issues among different countries in the Middle East (Allan, 2002). In the Yellow River, The State Council of China allocates 37 billion (10^9) m^3 of river flow each year to 9 provinces in the Yellow River basin, and Hebai and Tianjin that lie outside the basin, and reserves 21 billion $m^3\,yr^{-1}$ for delivering sediment to the sea through the Water Allocation Executive Order of 1987 (Chen et al., 1998). Due to its historical context, this type of basin scale allocation often gives little consideration to instream water needs for fisheries and wildlife habitat and for recreational activities. At the subwatershed or local scale, a variety of mathematical models and decision support systems have been used to allocate water among competing uses, including agricultural irrigation, wetland restoration, recreation, wildlife habitat, and environmental protection (Gisser et al., 1979; Goulter and Castensson, 1988; Hansen and Hallam, 1990; Duffield et al., 1992; He, 1997, 1999a,b; Yates et al., 2005; Sisto, 2009; Yang, 2011).

Studies have related streamflow levels to economic net benefits to determine appropriate allocation of flows among competing needs for irrigation, municipal water supplies, hydropower generation, and recreational uses such as fishing and boating

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in the Western US (Gisser et al., 1979; Duffield et al., 1992; Leones et al., 1997). He (1999a,b) incorporated climate variability, streamflow variations, soil characteristics, and crop net returns in allocating flows between agricultural irrigation supply and water quality management in the Eastern US. Yates et al. (2005) linked a hydrologic model with a linear programming model to allocate water across multiple competing demands in the Sacramento River of Northern California, USA. Rosenberg et al. (2008) developed a regional hydroeconomic model to simulate the effects of installations of water-efficient appliances, leak reduction in the distribution system, surface and groundwater development, seawater desalination, conveyance, and wastewater treatment projects on water resources in Jordan, and report that water conservation by urban users alone generates substantial regional benefits and can delay the need for infrastructure expansions. Sisto (2009) computed economic compensation amounts for farmers to release more water allocated for irrigation to maintain required environmental flows in a northern Mexico watershed. Yang (2011) used a multi-objective optimization approach to allocate environmental flows to the artificially restored wetlands in the Yellow River Delta in Northern China.

In recent years, a number of international programs such as the 1992 Dublin Statement from the International Conference on Water and the Environment, and the 1992 Agenda 21 from the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil have called for integrated water resources management (IWRM), defined as systematic consideration of water supplies and water demands, natural and human systems, and upstream and downstream linkages in development and implementation of water resources policies and decisions, as well as stakeholder participation in water resource management processes (Global Water Project, 2004; Snellen and Schrevel, 2004). While IWRM concept is globally accepted, models for operationalizing IWRM differ among regions and countries. In the US, watershed-based approaches are being used to manage the nation's water resources at the local, state, and federal levels for maintaining ecological integrity of the watersheds while achieving social justice and economic development. Stakeholder participation, often in the form of public hearing and comments, occurs at all stages of water resource planning and management (NRC, 1999, 2004; Matondo, 2002). An example is the Tennessee Valley Authority (TVA), an independent federal agency that is responsible for flood control, navigation development, electricity generation, natural resource conservation, and economic development within the Tennessee River Basin (NRC, 1999). In Europe, the European Union Water Framework Directive promotes technology-oriented approach for water resources management including water quality, river basin management, and emission control, but omitted gender awareness and poverty alleviation (Rahaman et al., 2004). In Africa, particularly in Southern African countries, the top priority of implementing IWRM is to provide access to reliable and affordable water for poverty alleviation and livelihood improvement (Mazvimavi et al., 2008). In Brazil, water governance systems with dominant use of technical knowledge are able to make rapid decisions under uncertainties and surprises (Engle et al., 2011).

Similar to Brazilian examples, Chinese IWRM is also dominated by command and control or centralization of technical expertise. Water allocation plans are usually drafted by technical experts first, and then submitted to sector governmental agencies for consideration and recommendation, and finally the water allocation plan is submitted to provincial and central governments for approval (Ding, 2004; Engle et al., 2011). The central government administers the nation's water resources through the Ministry of Water Resources (MWR) and provincial governments. Across the nation, there are 7 river basin commissions such as the Yellow River Conservancy Commission and the Yangtze River Commission, etc. These seven commissions are responsible to administer planning, development, flood control, water allocation and transfer, and boundary water conflicts (Ding, 2004). The provincial governments are in charge of the water resources affairs within the provincial territory. For river basins that across multiple provinces, water resources are jointly managed with the river basin commissions (Ding, 2004). The advantages of such IWRM systems include: (1) high efficiency, (2) fast response to water resource emergencies, (3) sound technical knowledge, (4) better consideration of multiple water demands, and (5) rapid enforcement of water regulations (Ding, 2004; Engle et al., 2011). For example, with the close coordination among the river basin commissions and provincial governments, China has successfully addressed the desiccation problems of the Yellow River and Tarimu River, ensuring the delivery of water downstream for ecosystem rehabilitation (Ding, 2004). The limitations of such models include: (1) inadequate consideration of stakeholder interest, (2) lack of stakeholder participation, and (3) absence of feedback mechanism (Engle et al., 2011; Rahaman et al., 2004).

One of the goals of water resource management is to develop and implement policies, processes, technologies, and organizations for understanding, distributing, and improving the movement and characteristics of water resources to meet the multiple needs of human societies and ecosystems in a socially responsible, economically viable, and environmentally sustainable way (He et al., 2005, 2010). Thus, water allocation needs to integrate natural (e.g. complex ecosystems) and human systems (e.g., multiple levels of organizations and stakeholders) to ensure sustainable water resource development with positive economic benefits and social welfare (He et al., 2000; Kidd and Shaw, 2007). While still evolving, water allocation studies in the literature often are sector oriented and give inadequate consideration to upstream and downstream linkages, and stakeholder participation in the water allocation process (He, 1999; He et al., 2000, 2007; Matondo, 2002; Snellen and Schrevel, 2004), particularly in water stressed arid regions. This paper develops a framework for allocating river flow among the upper, middle, and lower reach users in arid regions. It first describes the water allocation framework in arid regions, and then uses an example of the Heihe watershed in arid Northwestern China to illustrate the application of the framework. The Distributed Large Basin Runoff Model (DLBRM) was adapted to the Heihe watershed for understanding the hydrologic processes of the watershed and thereby providing a partial basis for implementing the central government's water allocation plan. Subsequently, the paper discusses the needs for monitoring and evaluation of water resources, and stakeholder involvement for a successful implementation of the water allocation plan in the Heihe watershed.

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2 Water allocation framework in arid watersheds

Arid areas are characterized by scarce and unpredictable precipitation, account for approximately 41 percent of the global land surface, and are home to over 2.5 billion people (Reynolds et al., 2007). In arid watersheds, competition for water among the upper, middle, and lower reach users is often intense and increasing. During the past few decades, improper water resource management has resulted in numerous problems worldwide, including poor food security, increased human diseases, conflicts between different users, limitations on economic development and human welfare, desertification, salinization, sand storms, and water pollution (UN World Water Development Report, 2003; Reynolds et al., 2007). In the Great Plains of the US, for example, the depletion of groundwater for agricultural irrigation, together with increasing pumping costs and low crop prices, has forced farmers to take 1 million ha of land out of irrigation (Postel, 1999). In Northern India, large scale overexploitation of groundwater for intensive irrigation had caused water table decline on average 4 cm each year between 2002 and 2008, and many aquifers in the nation are depleted (Postal, 1999; Keer, 2009). In Central Asia, increasing irrigation demands have resulted in reducing the area of the Aral Sea, once the world's fourth largest lake, by 50 percent and lowering its water level by 16 m, thus depleting fisheries and wildlife habitat, endangering flora and fauna, and increasing respiratory and digestive diseases from inhalation and ingestion of blowing salt and dust (Micklin, 1994). In China, increased withdrawals from the upper and middle reaches of the Yellow River depleted groundwater in much of the basin and contributed to the desiccation (i.e. no measurable flow in the river) of the lower reaches in 22 of the 28 yr between 1972 and 2000. This desiccation had created serious economic and environmental problems throughout the North-Central China, including water rationing, under-capacity industrial production, reduced crop yields, water pollution, wildlife endangerment, coastline recession, and sea water intrusion (He et al., 2005, 2010). In arid Northwestern China, irrigated farming accounts for more than 80 percent of total water usage. Increased withdrawals of streamflow upstream have depleted much of the river flows downstream, shrinking lakes, accelerating desertification, and intensifying water conflicts between the upstream and lower reach users in the Heihe, Shiyang, and Tarim watersheds (Cheng et al., 1999; Feng et al., 2002; Pan and Tian, 2001; Jia et al., 2005).

Climate change has direct impact on water resource management. In the past decade, western North America has experienced many signs of climate change, including declining late season snowpack, the worst drought in the measured record of the region, and steep declines in Colorado River reservoir storage. Over the course of this century, the region could become much hotter and drier (Overpeck and Udall, 2010). Immerzeel et al. (2010) studied the impacts of climate change on snow and glacial melt in the Tibetan Plateau and adjacent mountain ranges, and reported that climate change is likely to reduce upstream water supply in the Indus, Ganges, Brahmaputra, and the Yangtze Rivers. The reduced water availability will threaten food security of over 6 million people in these basins. In the Yellow River basin, climate change is simulated to increase upstream discharge and hence to enhance food security in the basin (Immerzeel et al., 2010). In the Heihe River watershed, an analysis of meteorological and hydrologic data showed a warming trend in the upper reach of the watershed over the past 50 yr, causing increased snowmelt runoff, particularly from 1970 to present (Wang et al., 2010). Such climate effects add further complexity and uncertainty in water resources management and need to be taken into consideration in the water resource allocation process.

This paper proposes a water allocation framework in arid watersheds (Fig. 2). As shown in Fig. 2, net water supply in an arid watershed is often a combination of precipitation and glacial melt in the upper reaches. The symbols, S, P, R, ET, G, and W represent supply, precipitation, surface runoff, evapotranspiration, groundwater, and water balance, respectively, with subscripts “u”, “m”, and “l” representing upper, middle, and lower reaches, respectively. A hydrologic analysis needs to be conducted to understand the spatial and temporal distribution of P, R, ET, and G in the upper, middle, and lower reaches. Net supply (a combination of precipitation and glacial melt),

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S_u, represents the water supply to the upper reach, the main runoff generation area. Surface runoff, R_u, from the upper reach is the main source of water supply for the middle reach agricultural oasis system, where agricultural irrigation (ET_m) is the main water user and a portion of surface water percolating to the aquifer (G_m) may flow to the lower reach where its vegetation is dependent upon the released flow or irrigation return flow from the middle reach for the vitality. Annual precipitation in the lower reach desert system is negligible. Thus the water balance W_l is the balance between the river flow (R_m) from the middle reach and the groundwater change (G_l) and ET_l from the vegetated areas, wetlands, lakes, and barren land along the river. If the flow from the middle reach is unable to meet the ET_l, then the river would cease to flow at the irrigation withdrawal points, the vegetated areas would shrink, lakes would go dry, and desertification would expand, as is the case in the past 50 yr in the Heihe watershed.

Completion of the hydrologic analysis is only the first step. The subsequent steps involve (1) allocation criteria, and (2) allocation implementation. The allocation criteria include climatic, hydrologic, economics, ecosystem, and social criteria (variables). For example, how does climate change affect the variability of net supply? How much water should be allocated to what uses and for whom? How to value and prioritize water uses for economic development, ecosystem services, and social equity? These criteria should be discussed, debated, and agreed upon among multiple stakeholders at federal, state/provincial, and local levels through proper organizations (e.g. watershed commission, water user association) in a participatory decision making process. Subsequently, the water allocation decisions should be implemented, monitored, evaluated, and revised according to changing natural processes and management conditions. A new water allocation cycle then begins. The advantages of such a framework include: (1) spatial integration; (2) multiple objectives; (3) incorporation of local needs through participatory decision making; and (4) dynamic evaluation (He et al., 2000; 2005, 2007, 2010; Snellen and Schrevel, 2004). The proposed framework, once verified with in situ data, can be transferred to other similar arid watersheds for addressing water allocation and management issues among the upper, middle, and lower reach users at the watershed scale.

3 Methods

3.1 The study area

The Heihe watershed is the second largest inland river (terminal lake) in the nation, with a drainage area of 128 000 km^2 (Fig. 1). It is used as a case study for application of the water resource allocation framework. From the headwaters in the south to the lower reach in the north, the Heihe watershed physically consists of the Qilian Mountain, the Hexi Corridor, and the Alashan Highland (Fig. 1). The Qilian Mountain is situated at the south of the watershed, with a peak elevation of 5584 m. Ice and snow remain year round above 4500 m. Mixed alpine meadow and permafrost dominate between 3600 to 4500 m. While the main vegetation is grassland and forest with a mean annual precipitation of 250–500 mm in the 1900–3600 m range, the landscape below 1900 m is dominated by hilly or grassland desert with a mean annual precipitation of 200–250 mm (Fig. 3) (Pan and Tian, 2001; He et al., 2009). Located in the middle reach of the Heihe watershed, the Hexi Corridor hosts over 90 % of the total agricultural oases in the watershed and supports more than 97 percent of the Heihe watershed's 1.8 million inhibits in two metropolitan areas: Zhangye (population 1.25 million in 2000) and Jiuquan (population 0.49 million in 2000). Irrigation supply is from both surface water withdrawals and groundwater pumping. North of the Hexi Corridor is the Alashan Highland (the area north of Zhengyixia with mean elevation 1000 m), an extremely dry desert with an annual precipitation below 50 mm. Spotty oases appear intermittently along the streams, lakes, and irrigation ditches. Since it is extremely dry, the Alashan Highland is a large source of frequent sandstorms (Cheng et al., 1999; Feng et al., 2002; He et al., 2009).

Over 86 % of the water withdrawals in the Heihe watershed were used for irrigating farmland mainly located in the middle reach Hexi Corridor (Pan and Tian, 2001; He et al., 2009). Since the 1970 s, the increased withdrawals for agricultural irrigation in the Hexi Corridor have depleted much of the river flows to the lower reach, shrinking the East Juyan Lake and drying up the West Juyan Lake, endangering aquatic ecosystems, accelerating desertification, intensifying water conflicts between the middle reach of Gansu Province and lower reach of the Inner Mongolian Autonomous Region (IMAR), and damaging relationships among Han, Mongolian, and Hui ethnic groups (He et al., 2009) (Figs. 1 and 3). To mitigate the water conflicts and rehabilitate West Juyan Lake, the State Council of China (the executive branch of the central government) has issued a "Water Allocation Plan for the Heihe Watershed Mainstream", mandating the allocation of 0.95 billion (10^9) m^3 of water annually to the lower reach under normal climatic conditions for rehabilitation of downstream ecosystems. Implementation of such a mandate means reducing the current water use for agricultural irrigation (potentially taking about 40 000 ha of farmland out of irrigation) in the City of Zhangye alone in the middle reach (Pan and Tian, 2001; The City of Zhangye, 2004), a potential loss of multiple million dollar revenue annually for the city. No action, however, would mean the continuing deterioration of ecosystems in the lower river reaches (He et al., 2009).

While a number of studies have been done in the Heihe watershed (Cheng et al., 1999; Feng et al., 2002; Pan and Tian, 2001; Jia et al., 2005), the magnitude, spatial and temporal distribution, and transfer mechanism of the Heihe hydrologic system are still not well understood. For example, are the flows from the upper and middle reaches sufficient to deliver 0.95 billion (10^9) m^3 of the water downstream annually?

3.2 Description of the DLBRM

To determine the amount of flows downstream from the upper and middle reaches (at the Zhengyixia hydrologic gauge station), this study uses the Distributed Large Basin Runoff Model (DLBRM) to simulate the hydrology of the Heihe watershed. Analysis

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of the 1945–1998 hydrologic data by Wu et al. (2010) shows the 1990–1998 as the normal period; 1970–1979 as the dry periods; and 1980–1989 as the wet periods. Due to the constraints of availability of the climatic and hydrologic data, this study chose the 1978–1987 as the calibration period and the 1990–2000 (normal flow period) as the simulation period (He et al., 2009).

The DLBRM was developed by the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory and Western Michigan University. It represents a watershed by using 1 km^2 (or other size) grid cells. Each cell of the watershed is composed of moisture storages of the upper soil zone (USZ), lower soil zone (LSZ), groundwater zone (GZ), and surface, which are arranged as a serial and parallel cascade of "tanks" to coincide with the perceived basin storage structure (Fig. 4). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration (ET). The model computes potential ET from a heat balance, indexed by daily air temperature, and calculates actual ET as proportional to both the potential and storage. It allows surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages. The model has been applied extensively to riverine watersheds draining into the North America's Laurentian Great Lakes for use in both simulation and forecasting (Croley and He, 2005, 2006; Croley et al., 2005; He and Croley, 2007a, b). The unique features of the DLBRM include: (1) use of readily available climatological, topographical, hydrologic, soil, and land use databases; (2) applicability to large watersheds; and (3) analytical solutions for mass continuity equations (mathematical equations are not shown here due to space limitations; for details, see Croley and He, 2005, 2006; He and Croley, 2007a,b).

The DLBRM requires 16 input variables for each of the grid cells (Tables 1 and 2). To facilitate the input and output processing for the DLBRM, an ArcView-DLBRM

(AVDLBRM) interface program has been developed to assist with the model implementation. The interface was written in ArcView Avenue scripts by modifying the ArcView Nonpoint Source Modeling interface by He and his colleagues (He et al., 2001; He, 2003; He and Croley, 2007b). It consists of six modules: (1) Soil Processor, (2) DLBRM Utility, (3) Parameter Generator, (4) Output Visualizer, (5) Statistical Analyzer, and (6) Land Use Simulator. Multiple databases of meteorology, soil, DEM, land use/cover, and hydrology and hydrography are used by the interface through the draw-down menu to derive input variables for the DLBRM (He et al., 2001; He, 2003; He and Croley, 2007b) (Tables 1 and 2). DLBRM outputs include, for every cell, surface runoff, ET, infiltration, percolation, interflow, deep percolation, groundwater flow, USZ, LSZ, groundwater, and surface moisture storages, and lateral flows between USZ, LSZ, groundwater, and the surface (Tables 1 and 2). The outputs can be examined either in tabular or map format using the interface.

3.3 DLBRM input data

The upper and middle reaches of the Heihe watershed were discretized into a grid network of 9790 cells at 4 km^2 resolution. Multiple databases of DEM (at 100 m resolution), land use/cover for the year 2000, meteorological and hydrologic databases for 1978 to 2000 were provided by The Chinese Academy of Sciences (CAS) Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) (Tables 1 and 2). These databases were used to derive relevant input variables for the DLBRM using the AVDLBRM interface for each grid cell (Croley and He, 2005; He and Croley, 2007b). Meteorological data sets for the period of 1978–2000 were spatially interpolated for every cell in the watershed by using inverse squared distance from each of the 13 weather stations adjacent to the study area (Fig. 1). Hydrologic data from 4 gauge stations (for the same period of 1978–2000) were used in the calibrations (Fig. 1). Since the soil database of 1999 (1 : 250 000) from the Gansu Province only contained soil types, we used SPAW (Soil-Plant-Atmosphere-Water) Field and Pond Hydrology model (developed by the US Department of Agriculture Agricultural Service and Natural Resources

Conservation Service) to estimate relevant soil attributes for each of the soil types in the Heihe watershed based on soil survey data collected by Xiao (2006) and his group (Chen and Xiao, 2003). Such attributes include soil texture, depth (cm) of USZ and LSZ, water holding capacity (%) and permeability ($\text{cm}\,\text{h}^{-1}$) (Figs. 3 and 5). Manning's coefficients were assigned to each cell by the hydrologic response units (HRU), which was determined according to the combination of land use, soil texture and slope (He and Croley, 2007b). Average daily river flow rates (in $\text{m}^3\,\text{s}^{-1}$) were converted into daily outflow volumes and used to conduct a systematic search of the parameter space to minimize the root mean square errors (RMSE) between actual and simulated daily outflow volumes at the watershed outlet (Croley et al., 2005; Croley and He, 2006).

3.4 Model calibration

The DLBRM was calibrated over the period of 1978–1987 (a wet hydrologic period) for each of the 9790 cells (cell size: 4-km^2) at daily intervals. The calibration consists of a systematic search of the parameter space to minimize the root-mean-square error between actual daily outflow volumes and model outflow volumes. The search consists of minimizing this error for each parameter, selected in rotation, until convergence in all parameters to two or three significant figures is achieved (Croley et al., 2005). The calibration module in the DLBRM can also be used to maximize sample correlation between actual and model daily flow volumes. The calibration periods are summarized in Table 3.

The calibration shows a 0.690 correlation between simulated and observed watershed outflows. The ratio of model to actual mean flow (μ_M/μ_A) was 1.014 (Table 3). Over a separate verification period (1990–2000, a normal hydrologic period), the model demonstrated a 0.710 correlation between simulated and observed watershed outflows, and the ratio of model to actual mean flow was 1.409 (an overestimation by 40 percent). To take into account surface water supply from snow and glacial melt, a 10.85 m of snow pack was assumed in about 305 km^2 of upper reach mountain area (elevation > 4500 m) in the simulation. All the assumed snow was melted within

2 months in the simulation and the result was quite similar to the ones without added snow pack (Table 3).

The simulated annual water budget (averages of the 1990–2000) shows that annual surface net supply from both rainfall and snow melt was about 8.92 billion (10^9) m^3 (Fig. 6), which mainly came from Qilian Mountain in the upper reach. The USZ (a conceptual layer accounting for the upper few centimeters of the soil) stored about 391 billion m^3 of water, the largest storage among all the four storage tanks (USZ, LSZ, groundwater zone, and surface storage). Surface runoff from the USZ averaged about 0.54 billion m^3, while a much larger portion of water (8.37 billion m^3) percolated down to the LSZ. A majority (94 %) of the percolated water evaporated to the atmosphere from the LSZ and the rest flowed to the stream in the form of interflow. There was hardly any deep percolation to the groundwater since the LSZ is up to 1000 m deep in the middle reach area (Pan and Tian, 2001; Wu et al., 2010). The average annual outflow at the outlet (Zhengyixia) of the middle reach was about 1.05 billion m^3 to the downstream (Fig. 6).

Figure 7 shows the general behavior of the watershed in response to the 24–26 July 1990 rainfalls. The supply, evaporation, percolation, and surface runoff (all in $\mathrm{cm\,day^{-1}}$) are within-the-cell flows, and the outflow is the accumulated flow down the flow network, much larger than within-the-cell flows. The supply was low on 24 and 26 July but was up to 4 $\mathrm{cm\,day^{-1}}$ (Fig. 7). Surface runoff flew out of the upper soil zone into the surface zone, interflow flew from the lower soil zone to the surface zone, and outflow flew from the surface zone and accumulated downstream. There was no groundwater flow, implying that only the two responses (from the USZ and LSZ) could be detected in the data (Croley and He, 2006). Over the three-day period, the evaporation didn't change significantly, but percolation, surface runoff, and outflow responded quickly. On 25 July, the supply amount was up to 4 $\mathrm{cm\,day^{-1}}$, showing a pattern of higher rate in the Qilian Mountain (south or lower portion area) and gradually lowering the rate toward the middle reach oasis (north or upper portion area) (note: the three bright spots and one dark spot on the supply map represent the locations of the weather stations with the greater rainfall rates in the mountain area and the lower rainfall rate in the middle reach oasis, respectively) (Fig. 7). Percolation and surface runoff increased fast, especially in the mountain area. Outflow reached a maximum of 372 cm day^{-1} over the 4 km^2 surface area at the mountain outlet, forming a denser outflow network, but declined toward the middle reach outlet. When the supply was low on 24 and 26 July, the corresponding evaporation and surface runoff were also low, but percolation continued to increase due to accumulated water in the upper soil zone, while outflow declined on 26 July due to less supply than that on 25 July (Fig. 7).

3.5 Discussion

The simulation results show that the Qilian Mountain (up to 5584 m above sea level) in the upstream generates the majority of the water supply and flow in the entire Heihe watershed (Figs. 6 and 7). Vegetation in the area consists of mainly meadow, grassland, forest, and cold desert (Fig. 3). Due to the high altitude and steep slope of the mountain area, much of the snow melt and rainfall becomes surface runoff (Cheng et al., 1999; Jia et al., 2005; Pan and Tian, 2001; Wu et al., 2010). Once reaching the mountain outlet (Yingluoxia), the water quickly infiltrates to the alluvial fan deposits that consist of gravel, sand, and clay, with a depth ranging from 300 to 700 m, even up to 1000 m (Fig. 5) (Wu et al., 2010).

As annual precipitation in the middle reach (between the mountain outlet – Yingluoxia and the middle reach outlet – Zhengyixia) is less than 200 mm, the river flow is used to irrigate crops like spring wheat, corn and rice in the main agricultural oasis. A main portion of the irrigation water is returned to the atmosphere through evaporation, and irrigation return flows percolate to the groundwater zone and then flow to the river (Pan and Tian, 2001; Wu et al., 2010). As shown in Fig. 6, nearly 94 percent of the net supply was simulated to percolate to the lower soil zone. There was little deep percolation to the groundwater. Instead, a portion of the water in the LSZ was simulated to flow to the river channels though interflow. This is due to the fact that LSZ is several hundred meters deep and could be mixed with groundwater zone. Studies by Cheng

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et al. (1999), Jia et al. (2005), Pan and Tian (2001), and Wu et al. (2010) report similar findings that in the middle reach oasis area, river flow infiltrates to the alluvial fan, and then flows out to the river channel from the aquifer.

The simulation results show there was little evaporation from the upper soil zone. Instead, a very high evaporation rate occurred in the LSZ (Figs. 6 and 7). This phenomenon is attributable to several factors. First, the USZ is a conceptual storage layer with a simulated capacity of a few cm to up to 100 cm. Second, between the mountain outlet (Yingluoxia) and middle reach outlet (Zhengyixia), soil is quite coarse and sandy, and thus water from the USZ infiltrates to the LSZ quickly (Cheng et al., 1999; Wu et al., 2010) (Figs. 5, 6, and 7). Third, consumption of groundwater is mainly through evaporation in the middle reach of the watershed. Since the LSZ is several hundred meters deep and could be mixed with groundwater zone, loss of soil water and groundwater was simulated through the form of evaporation to the atmosphere in this study (Cheng et al., 1999; Jia et al., 2005; Pan and Tian, 2001; and Wu et al., 2010).

The DLBRM simulations reasonably depicted the water movement processes in the Heihe watershed and reported similar findings by other researchers (Cheng et al., 1999; Jia et al., 2005; Pan and Tian 2001; and Wu et al., 2010). The simulated average annual flow for 1990–2000 was about $1.05 \times 10^9\,\mathrm{m}^3$ at the middle reach outlet (at Zhengyixia) under a normal, median precipitation year ($P = 50\,\%$), which seems just sufficient to meet the requirement of delivering $0.95 \times 10^9\,\mathrm{m}^3$ downstream annually by the State Council 50 percent of the time. But the annual river flow was simulated to change from $0.80 \times 10^9\,\mathrm{m}^3$ in 1991 (a dry year, $P = 75\,\%$) to $1.27 \times 10^9\,\mathrm{m}^3$ in 1998 (a wet year, $P = 20\,\%$).

It should be noted that the simulations of 1990–2000 overestimated actual flow by 40 percent. While several factors are related to this discrepancy, it seems that the increased withdrawals were the main factor that contributed to the overestimation. Pan and Tian (2001) report that increasing agricultural, industrial, and municipal withdrawals in the middle reach had led to a declined flow by 0.266 billion $\mathrm{m}^3\,\mathrm{yr}^{-1}$ at the middle reach outlet between 1980 and 1995. In the upper and middle reaches of the

Heihe watershed, there are approximately 35 reservoirs with a combined effective storage capacity of 0.125 billion (10^9) $m^3\,yr^{-1}$ (Wu et al., 2010). Average withdrawal of groundwater for agricultural irrigation was about 0.162 billion (10^9) $m^3\,yr^{-1}$ for the period of 1990–1999. These two add to about 0.287 billion $m^3\,yr^{-1}$ (Wu et al., 2010). On the other hand, the average annual discharge measured at the Zhengyixia hydrologic gauge station was 0.769 billion $m^3\,yr^{-1}$ for the same period (Wu et al., 2010). The DLBRM simulated outflow at the Zhengyixia outlet was 1.054 billion $m^3\,yr^{-1}$, overestimating the actual discharge by approximately 0.285 billion $m^3\,yr^{-1}$, which was close to the combined reservoir storage and withdrawal of groundwater for irrigation (0.287 billion $m^3\,yr^{-1}$).

Moreover, the uncertainties in this study may also be related to the following factors: (1) Absence of meteorological databases in the high elevation area (above 3300 m). Daily precipitation and temperature input to the DLBRM were spatially interpolated from a network of 13 weather stations all located below 3300 m elevation, corresponding to about 3000 km^2/station. Such lack of detailed spatial representation of meteorological data leads to large uncertainties in parameter estimates and hence model output (Chaubey et al., 1999). (2) Poor spatial coverage of streamflow gauge stations. Surface runoff from tributaries in the upper reach mountain area and middle reach accounts for nearly all the river flow in the Heihe watershed. However, data from only four hydrologic stations were available and used in this study, and data from several major tributaries (e.g. Liyuan River) were not available to this study, causing inaccurate accounting of water budget. (3) Lack of detailed soil attribute database. The available soil database only contained spatial coverage of the 57 types of soils in the entire Heihe watershed. The related soil attributes such as texture and permeability were estimated from a number of sources including field soil survey data and literature. And (4) the spatial landscape data used in this study had multiple spatial resolutions. All those databases were aggregated to the 4 km^2 cells for use in this study. This aggregation process inevitably generates errors into the simulation results (He and Croley, 2007a; He et al., 2009).

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Work is under way to adjust daily precipitation and temperature databases by elevation to account for the effects of the elevation in the study area, and use finer grid cells (e.g. 1 km^2) to represent the study watershed in the simulations. After improving the simulation accuracy of the DLBRM, we will incorporate climate change (from the General Circulation Model results and regional climate models) and management scenarios into the model and assess how climate change and irrigation management (e.g. change of crop pattern) would affect the magnitude and distribution of surface runoff, groundwater, ET, and basin outflow in the study area (He et al., 2009; Thanapakpawin et al., 2006).

4 Allocation criteria

Hydrologic simulation is just the first step to understand the spatial and temporal distribution of the hydrologic processes in the study watershed. Besides hydrologic criteria (variables), climate change, economic, ecological, and social variables need to be used in comprehensive evaluation of the water allocation plan. Climate change directly affect water resources management and needs to be incorporated into water allocation process. For example, it is reported that climate change will increase upstream discharge and to enhance food security in the Yellow River basin (Huang and Zhao, 2004; Immerzeel et al., 2010; Yang et al., 2004). A warming trend over the past 50 yr has caused increased snowmelt runoff, earlier start of snow melting time, and shrinking glacier in the upstream of the Heihe watershed (Pan and Tian, 2001; Wang et al., 2010).

Economic analysis needs to address the benefit and cost of the water allocation for the upper reach, middle reach, lower reach, and the whole watershed, respectively. For example, if the water users in the middle reach reduce their withdrawals of water in order to deliver more water for downstream users, how much cost (economic loss) would they bear and how much benefit is to be gained by the downstream users? Are the aggregate benefits from the water allocation greater than the costs over the entire watershed (He et al., 2000; Kinzig et al., 2011)?

Ecosystem service analysis should define the amount of ecological benefits that would be produced by delivering more water downstream each year, particularly those intangible services such as desertification control, reduction of sand storms, watershed protection, habitat provision, water and air quality improvement, etc. (Kinzig et al., 2011). Researchers are just beginning to implement this type of analysis in China (He et al., 2010; Wang et al., 2010).

Social analysis should identify who benefits and who loses from the water allocation and propose fair compensation for those water users who take an economic loss. For example, if the middle reach water users are to be compensated for delivering more water downstream for rehabilitation of the downstream ecosystem, how should they get compensated and who pays for that, downstream water users or governmental entities? In the case of the Heihe watershed, governmental entities (e.g. Cities of Zhangye and Jiuquan) in the middle reach are taking a number of actions such as adjusting crop patterns, water pricing, and market transfer to deliver more water downstream, but comprehensive criteria are yet to be developed to address such questions related to the State Council's Water Allocation Plan (Cheng et al., 1999; Zhong and Mol, 2008).

5 Allocation implementation

Implementation of water allocation decisions involves formation of watershed organizations, stakeholder participation, and management of the plans.

(1) Formation of watershed organizations. As watersheds often across multiple administrative jurisdictions, proper forms of organizations need to be established to address important watershed scale issues such as water allocation among the upper, middle, and lower reach water users. Examples of such organizations are water management districts (e.g. water management districts in the State of Florida, the US),

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or river basin commissions (e.g. the Yellow River Conservancy Commission, and the Bureau of the Heihe Watershed Administration) (He et al., 2000, 2007).

(2) Stakeholder participation. Implementation of water allocation plan requires close interactions and strong partnerships between all stakeholders, such as federal, state/provincial, and local governments, industry, residents, community groups, and the research community (He et al., 2000). The water allocation plan should be discussed, debated, revised, and agreed upon among those stakeholders through a participatory decision making process to ensure the successful implementation of the plan at the watershed scale. In China, water resources decisions still dominantly reside with the central government agencies, and solicitation of participation of key stakeholders (e.g. county government agencies and local residents) in the water allocation process is often achieved through systematic interactions such as meetings (e.g. public hearings), surveys, and discussions with relevant stakeholders (Ding, 2004; Engle et al., 2011; He et al., 2000; NRC, 2004; Zhong and Mol, 2008). This form of public participation needs to be expanded to incorporate multiple needs of the upper, middle, and lower reach users in the watershed planning and management.

(3) Management of water allocation plans. Through the watershed organization (e.g., the Yellow River Conservancy Commission, and the Bureau of the Heihe Watershed Administration) (He et al., 2000, 2007), a management mechanism should be developed for operation, monitoring, and evaluation of water allocation plans (He et al., 2000). Information on operation of the water allocation plan should be timely exchanged with the stakeholders in the watershed. Multiple data sets of hydrology, land use, ecosystem, and social economics are to be systematically collected through scientifically designed monitoring plan over the entire watershed. Subsequently, these data are used to compute and compare the values of hydrologic, ecological, and socio-economic variables for evaluation of the performance of the water allocation plan for the upper, middle, and lower reach as well as the entire watershed, respectively. If comparison of the hydrologic, ecological, and socio-economic indicators between pre- and post implementation of the water allocation plan shows improvements, then the

allocation plan is able to meet the competing demands for water among the upper, middle, and lower reach users. Otherwise, the allocation plan is either unable to bring the anticipated comprehensive benefits to the watershed as a whole, or the conflicts between the upper, middle, and lower reach users are not alleviated. The water allocation plan needs to be modified. A new water allocation cycle begins (Engle et al., 2011; He et al., 2000; NRC, 2004).

Water allocation decision making in China is still dominated by command and control (Ding, 2004; Engle et al., 2011). While full implementation of the proposed water allocation plan has yet to take place at the watershed scale, the National Natural Science Foundation of China (NSFC, 2011) has started a large scale, multiple year research program, "Integrated research of eco-hydrologic processes in the Heihe Watershed". Its goals are to (1) understand the mechanisms and interactions of hydrologic and ecological processes at the watershed scale, (2) develop the watershed eco-hydrologic model, and (3) implement a decision support system for enhanced analysis and prediction of the variability of the hydrologic, ecological, and economic systems for sustainable uses of the water resources in the Heihe watershed. In the mean time, solicitation of local needs at local scales are also emerging (Engle et al., 2011; He et al., 2000; Zhong and Mol, 2008) in China. As the NSFC Heihe watershed program just started in 2011, no specific data are available to show the full implementation of the proposed water allocation framework in the Heihe watershed at present time. With the progress of the NSFC-Heihe watershed program, data will be available to show the implementation of the proposed framework. With verification and adaptation, the proposed framework can also be applied to other similar arid watersheds for facilitating the interaction between research and management communities in integrating scientific data and information into participatory watershed decision making processes for sustainable use of water resources (Engle et al., 2011; He et al., 2000; NRC, 2004; Zhong and Mol, 2008).

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6 Conclusions

Allocation of streamflow is one of important but often contentious resource decisions to satisfy multiple demands for water between both upstream and downstream users, especially in water stressed watersheds. This paper develops a framework for allocating river flow among the upper, middle, and lower reach users in the arid watersheds. The framework includes: (1) hydrologic simulation of distribution of water resources among the upper, middle, and lower reaches; (2) development of water allocation criteria; and (3) implementation of the water allocation plan. It was applied to the Heihe watershed in arid Northwestern China. Hydrologic simulations of the Heihe watershed by the DLBRM show that Qilian Mountain in the upper reach is the main runoff production area for the entire watershed. Over the 1990–2000 period (normal climatic period), the increased withdrawals of water for agricultural irrigation, industrial development, and municipal supplies at the middle reach oasis reduced the annual mean discharge downstream by approximately $0.18 \times 10^9\ \mathrm{m}^3$, unable to deliver the State Council mandated amount of $0.95 \times 10^9\ \mathrm{m}^3$ for the rehabilitation of downstream ecosystems. In addition, climate change and rapid urban expansion will further intensify the water shortage problem in the Heihe watershed. Thus, development of a comprehensive water management plan to address the competing demands for water among agricultural irrigation, industrial development, urban supplies, and ecosystem protection remains a long term challenge among water users in the upper, middle, and lower reaches of the Heihe watershed.

Based on the hydrologic simulation results, the paper suggests that a participatory watershed planning approach be taken to involve federal, provincial, and local stakeholders in the water allocation process to address some of the key questions: for example, how much water should be allocated to what uses and for whom and for how much? At present time, the proposed water allocation framework has yet to be fully applied to the Heihe watershed. However, through verification and adaptation with in situ data, the proposed framework has the potential to be applied to other similar arid watersheds to support sustainable use of water resources.

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Table 1. Input variables for the DLBRM, sourced from CAREERI.

Variables	Databases
Elevation (m)	Digital elevation model (DEM)
Flow direction	DEM
Slope (%)	DEM
Land use	Land use database
Depth of upper soil zone (USZ, cm)	Compiled soil database
Depth of lower soil zone (LSZ, cm)	Compiled soil database
Available water capacity (%) of USZ	Compiled soil database
Available water capacity of LSZ	Compiled soil database
Permeability of USZ (cm h^{-1})	Compiled soil database
Permeability of LSZ (cm h^{-1})	Compiled soil database
Soil texture	Compiled soil database
Manning's coefficient value	Land use, slope, and soil texture

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Table 2. Time series meteorological and flow variables for the DLBRM, sourced from CAREERI.

Variables	Databases
Daily precipitation	Gansu Bureau of Meteorology
Daily air temperature	Gansu Bureau of Meteorology
Daily solar isolation	Gansu Bureau of Meteorology
Daily flows	Gansu Bureau of Hydrology

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Table 3. DLBRM Heihe calibration statistics.

					Long-term average ratio to surface net supply				
Calibration period	Correlation	RMSE (cm)	μ_M/μ_A	σ_M^2/σ_A^2	Surface runoff	Interflow	Groundwater flow	Upper zone evaporation	Lower zone evaporation
1978–1987	0.690	0.007	1.014	0.683	0.065	0.061	0.000	0.000	0.884
1978–1987* with glacial	0.690	0.007	1.011	0.682	0.065	0.061	0.000	0.000	0.885
1990–2000	0.710	0.006	1.409	0.717	0.061	0.070	0.000	0.000	0.870

[*] A 10.85 m snow pack was assumed in about 305 km^2 of mountain area (elevation > 4500 m) in the simulation.
Note: RMSE, root mean square error.
μ_M/μ_A, ratio of modeled mean flow to actual mean flow volume.
σ_M^2/σ_A^2, ration of modeled flow variance to actual flow variance.

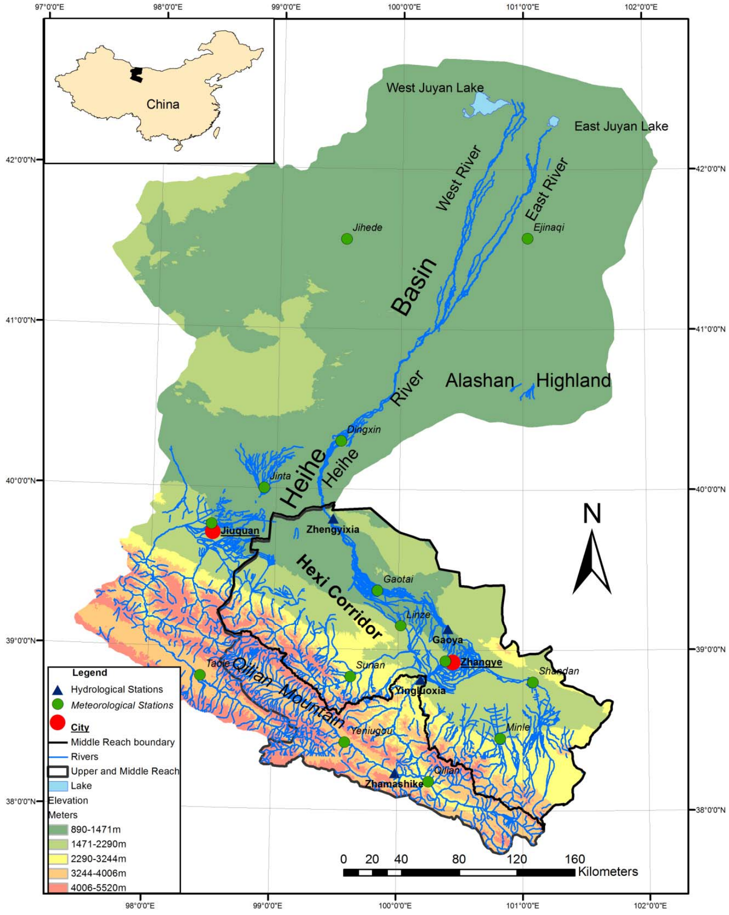

Fig. 1. Map of The Heihe watershed.

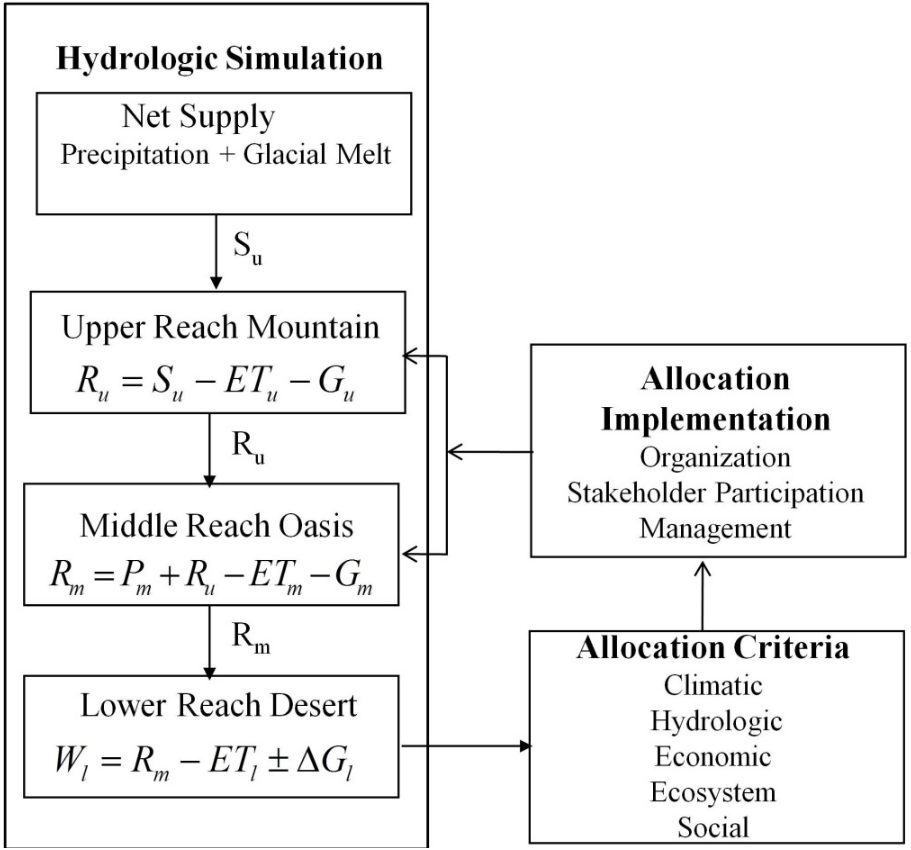

Fig. 2. A conceptual framework for allocation of river flow in arid watersheds.

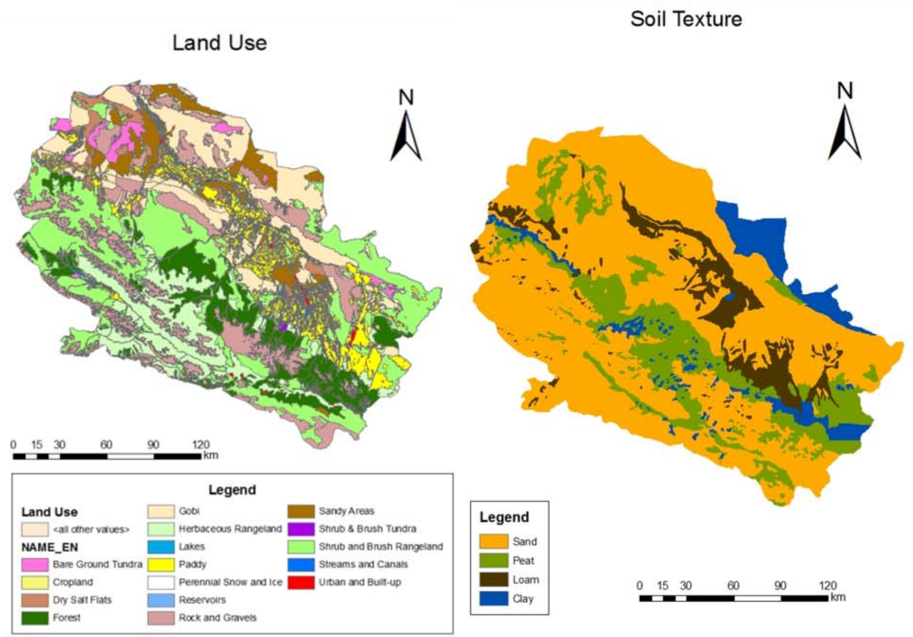

Fig. 3. Land use type and soil texture in the upper-middle reaches of the Heihe watershed.

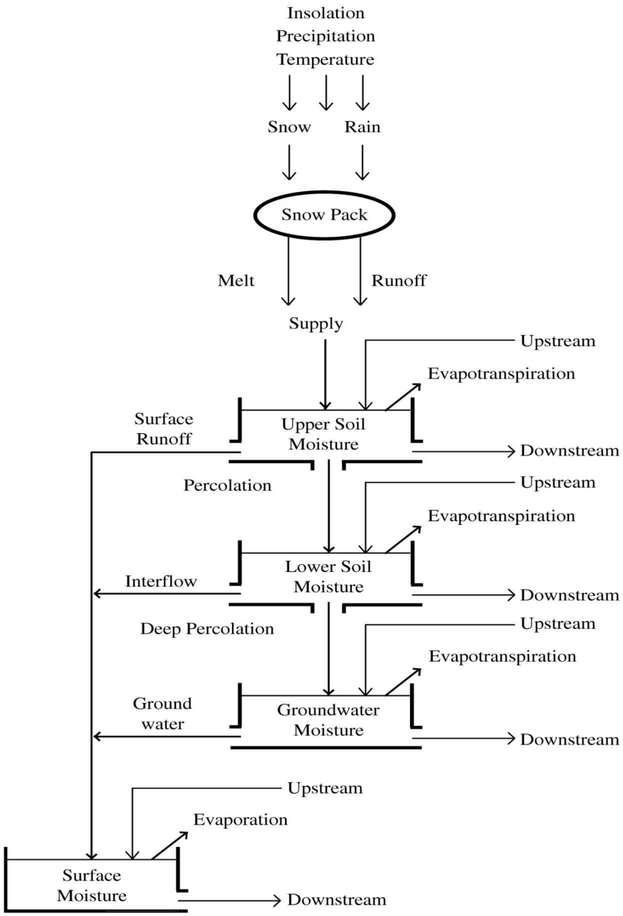

Fig. 4. Tank cascade schematic of Distributed Large Basin Runoff Model.

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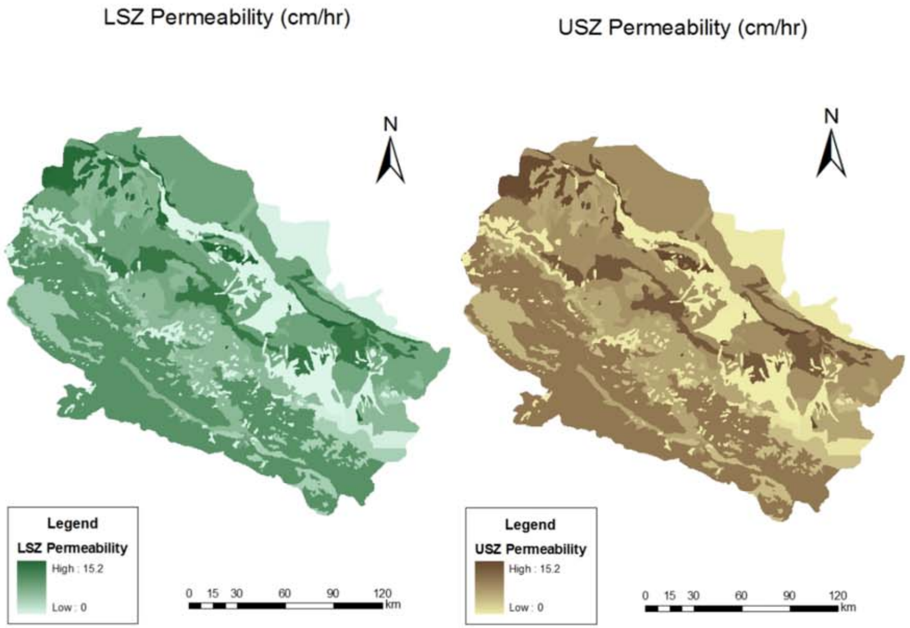

Fig. 5. Permeability of the upper soil zone (USZ) and lower soil zone (LSZ) in the upper-middle reaches of the Heihe watershed.

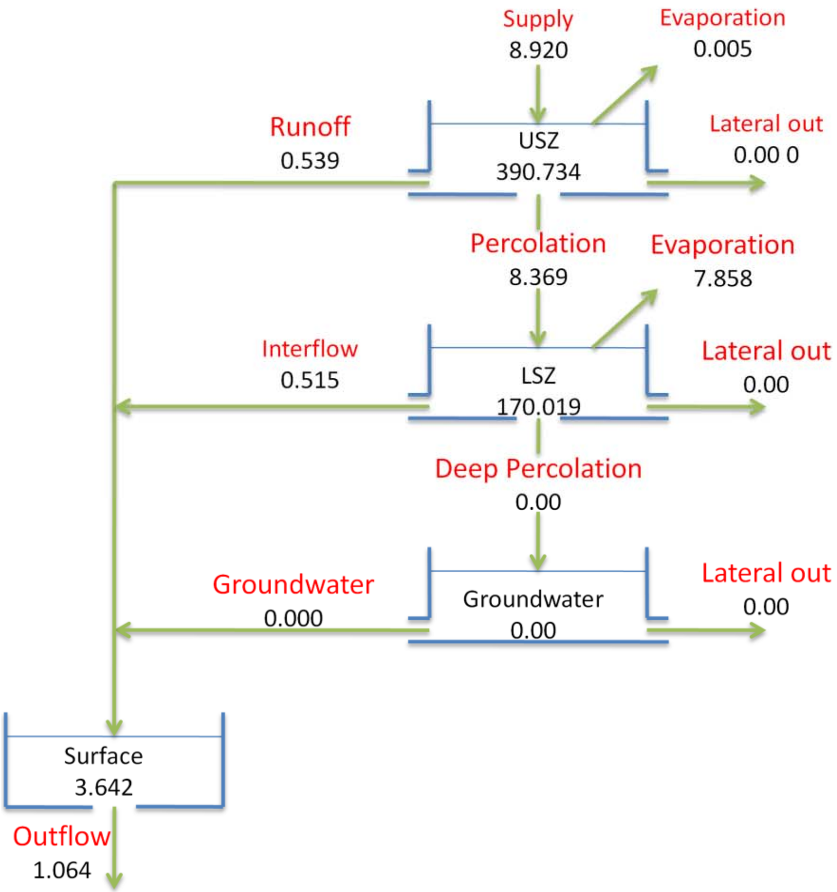

Fig. 6. Annual water budget (1990–2000 average in 10^9 m^3) for the upper-middle reaches of the Heihe watershed.

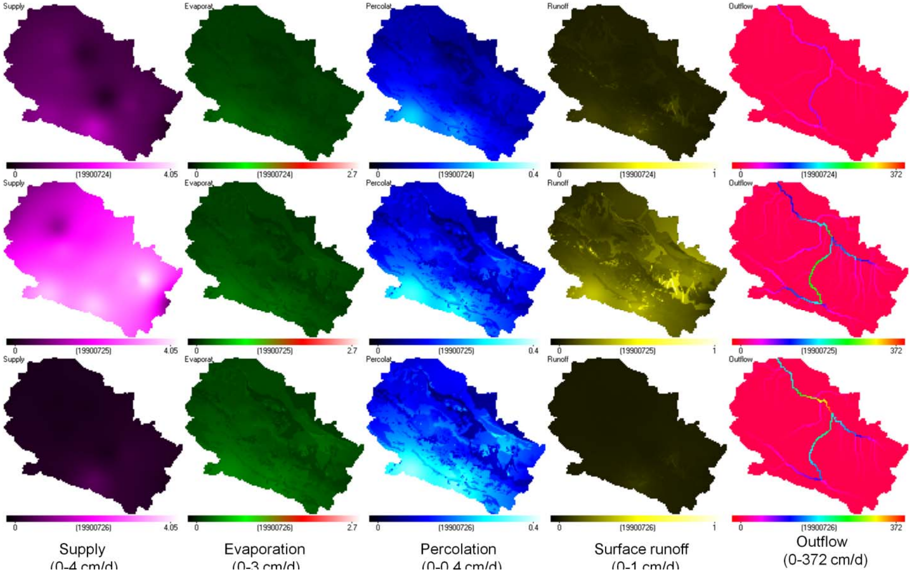

Fig. 7. Distributed DLBRM output for the upper-middle reaches of the Heihe watershed for the period of 24–26 July 1990.